Jet evolution in dense QCD matter

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Strong and Electroweak Matter 2016

Universitetet i Stavanger

Outline

1. **Motivations**

2. **Radiative correction to jet quenching parameter**

3. **Multiple branching and thermalization**

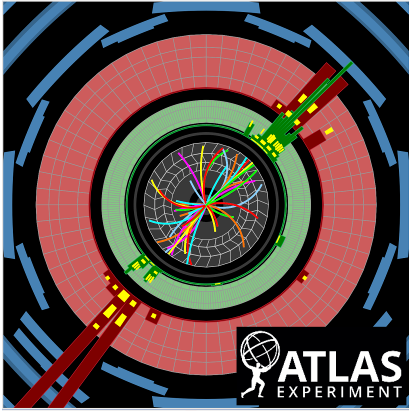
4. **Summary**

Liou, Mueller and BW, Nucl. Phys. A 916 (2013) 102-125;

BW, JHEP **1110**, 029 (2011); JHEP **1412**, 081 (2014);

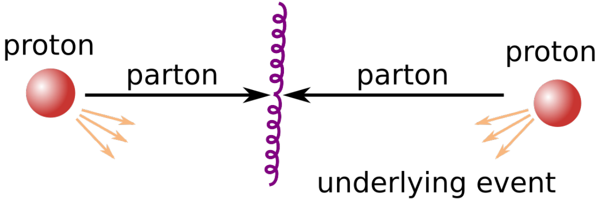
Iancu and BW, JHEP **1510**, 155 (2015).

1.1 Jets in proton-proton collisions



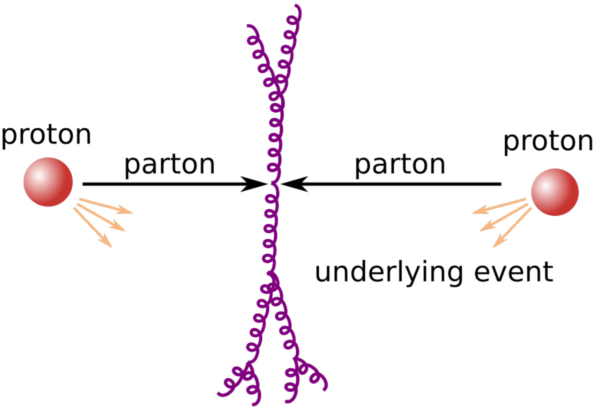
a dijet event recorded by ATLAS at the LHC

1.1 Jets in proton-proton collisions



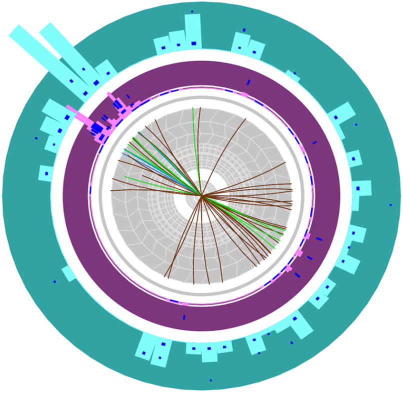
partons in a hard scattering process

1.1 Jets in proton-proton collisions



jet evolution in vacuum

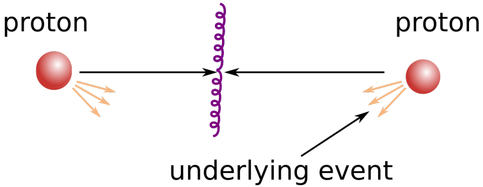
1.2 Jets in nucleus-nucleus collisions



an asymmetric dijet event in a PbPb collision

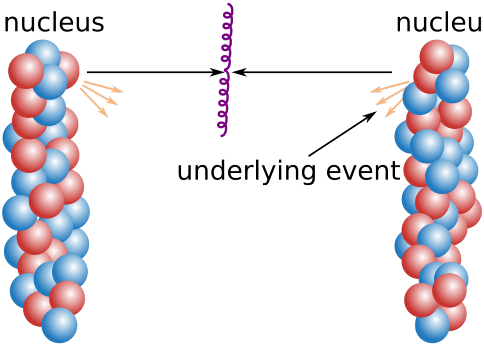
ATLAS, Phys. Rev. Lett. **105**, 252303 (2010).

1.2 Jets in nucleus-nucleus collisions



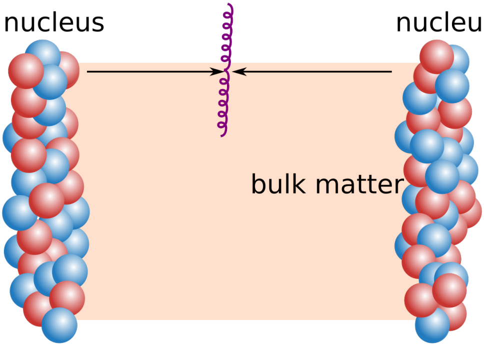
compare to a proton-proton collision

1.2 Jets in nucleus-nucleus collisions



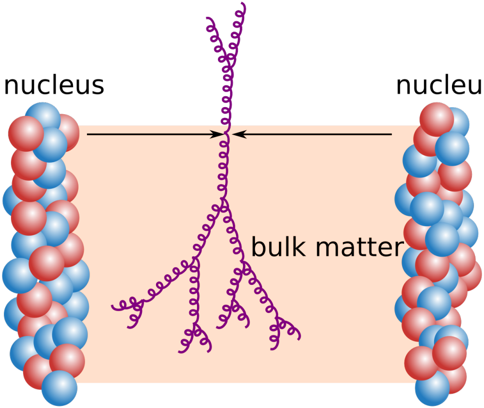
partons in a hard scattering process

1.2 Jets in nucleus-nucleus collisions



underlying event → bulk QCD matter

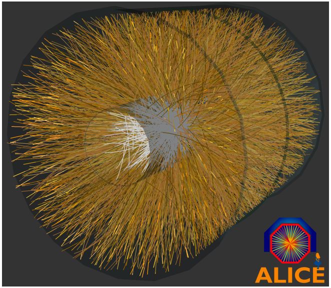
1.2 Jets in nucleus-nucleus collisions



jet evolution in bulk QCD matter

1.2 Jets in nucleus-nucleus collisions

Bulk matter in central PbPb collisions



- **Particles produced**

  $\approx 25{,}000$ at $\sqrt{s_{NN}} = 2.76$ TeV

- **Thermalization**

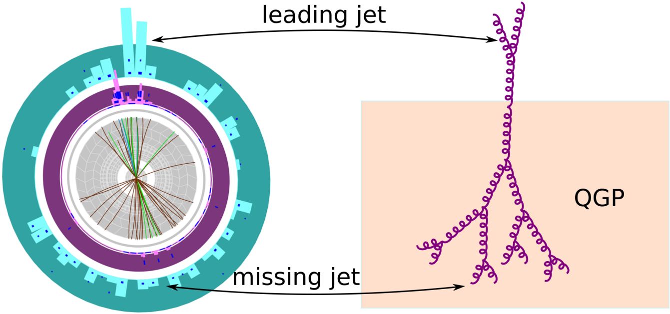
  Talks by Venugopalan & Kurkela.

Idealization

a quark-gluon plasma (QGP) with temperature T

1.3 Jets in QCD matter

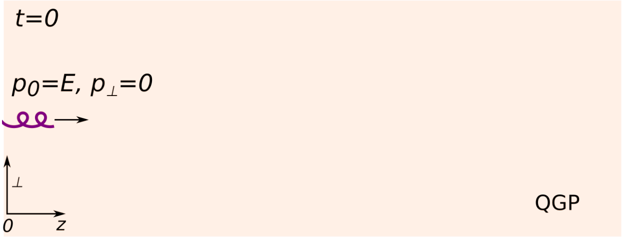
Aim of this talk: the entire evolution of a jet in a QGP



What does this figure mean?

1.3 Jets in QCD matter

What is the fate of a parton in a QGP?



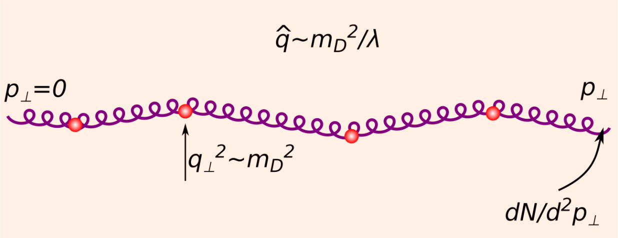
Properties of a hot QGP

$$m_D^2 \sim \alpha_s T^2, \qquad \sigma \sim \frac{\alpha_s^2}{m_D^2}, \qquad \lambda = \frac{1}{\rho\sigma} \sim \frac{1}{\alpha_s T}.$$

Arnold, Moore & Yaffe (2003).

1.3 Jets in QCD matter

1. Multiple scattering:

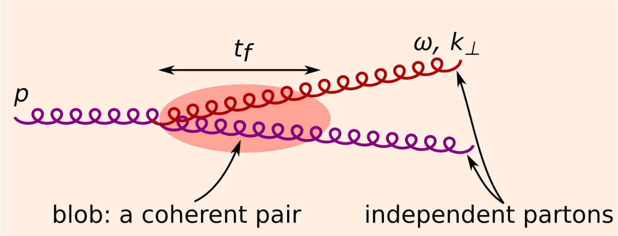


$$\frac{dN}{d^2p_\perp} = \frac{1}{\pi \hat{q} t} e^{-\frac{p_\perp^2}{\hat{q}t}} \Rightarrow \langle p_\perp^2 \rangle = \hat{q} t$$

Here, $\hat{q}$ is called **jet quenching parameter.**

1.3 Jets in QCD matter

2. Gluon radiation



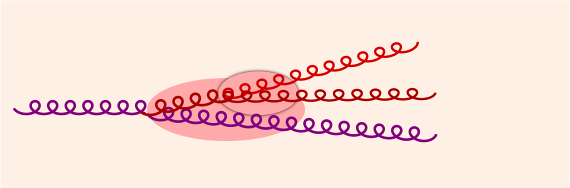
radiation occurs within the formation time

$$t_f = \frac{2\omega}{k_\perp^2}$$

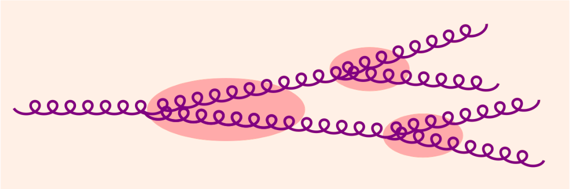
1.3 Jets in QCD matter

Topics of this talk

1. **Fully-overlapping emission:** radiative correction to $\hat{q}$

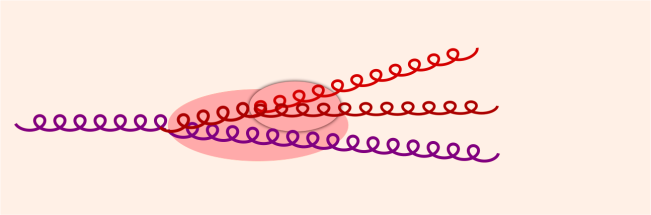


2. **Independent emission:** multiple branching & thermalization



2 Radiative correction to $\hat{q}$

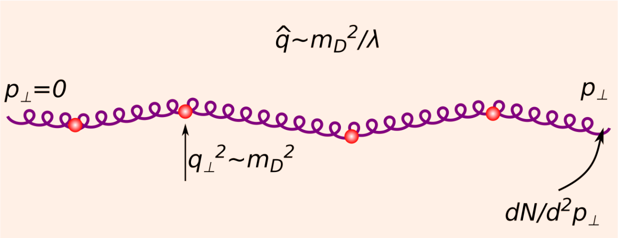
$p_\perp$-broadening: diffusion + the recoil of gluon radiation



Liou, Mueller and BW (2013); BW (2011, 2014).

2 Radiative correction to $\hat{q}$

Setup the problem: calculate typical $\langle p_\perp^2 \rangle$



$$\frac{dN}{d^2 p_\perp} = \frac{1}{\pi \langle p_\perp^2 \rangle} e^{-\frac{p_\perp^2}{\langle p_\perp^2 \rangle}} \text{ with } \langle p_\perp^2 \rangle = \hat{q} t$$

Multiple soft scatterings ($m_D \ll E$)

2 Radiative correction to $\hat{q}$

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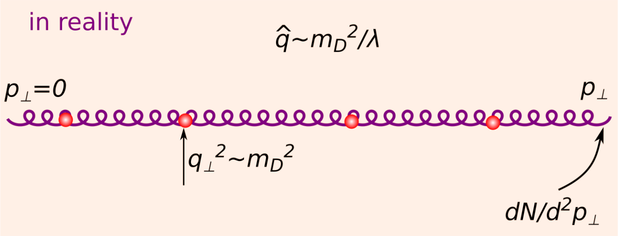

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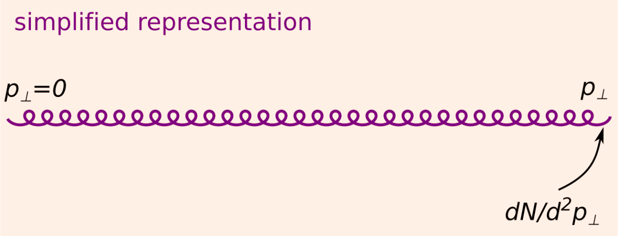
Small angle scatterings

2 Radiative correction to $\hat{q}$

Setup the problem: calculate typical $\langle p_\perp^2 \rangle$



$$\frac{dN}{d^2p_\perp} = \frac{1}{\pi\langle p_\perp^2\rangle} e^{-\frac{p_\perp^2}{\langle p_\perp^2\rangle}} \text{ with } \langle p_\perp^2\rangle = \hat{q}t$$

Multiple soft scatterings

2 Radiative correction to $\hat{q}$

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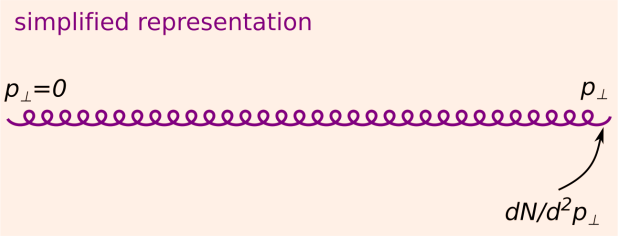

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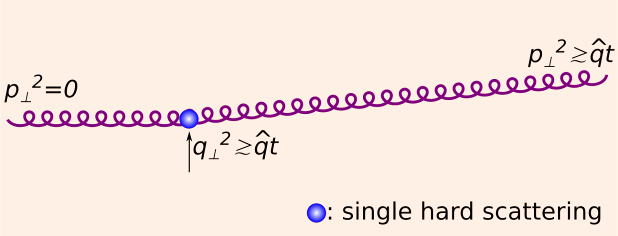
What is the contribution from recoil of gluon radiation?

2 Radiative correction to $\hat{q}$

Missing effect #1: (rare) single hard scattering

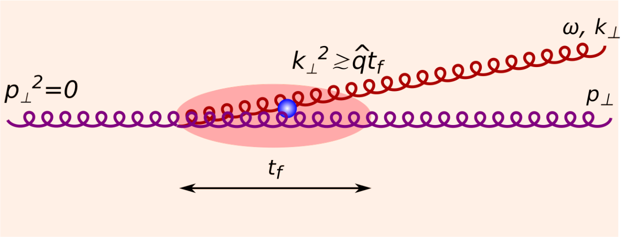


$$\frac{dN}{d^2p_\perp} \approx \frac{t}{\lambda}\frac{1}{\sigma}\frac{d\sigma}{d^2p_\perp} \propto p_\perp^{-4} \qquad \text{for } p_\perp^2 \gtrsim \hat{q}t$$

Does single scattering play any important role?

2 Radiative correction to $\hat{q}$

Single scattering of the coherent pair within t_f

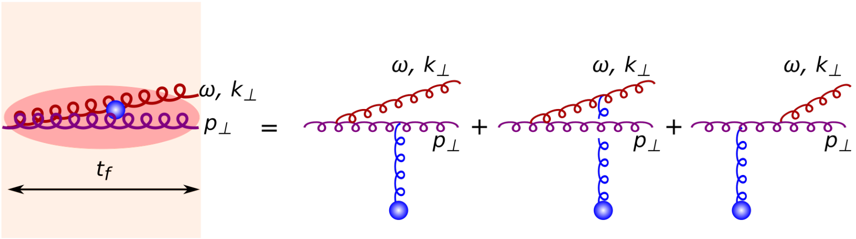


- kinematic region ($t_f = \frac{2\omega}{k_\perp^2}$)

$$k_\perp^2 \gtrsim \hat{q} t_f$$

2 Radiative correction to $\hat{q}$

Single scattering of the coherent pair within t_f

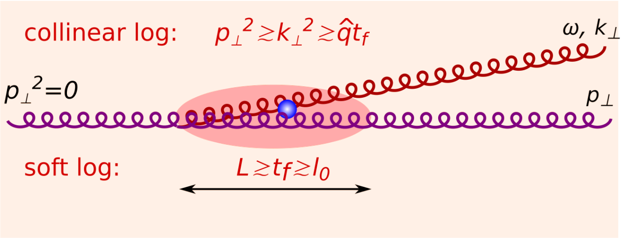


Soft & collinear divergences

$$\langle p_\perp^2 \rangle = \alpha \hat{q} L \underbrace{\int \frac{d\omega}{\omega}}_{\text{soft}} \underbrace{\int \frac{dk_\perp^2}{k_\perp^2}}_{\text{collinear}} \qquad \text{with } \alpha \equiv \frac{\alpha_s N_c}{\pi}.$$

2 Radiative correction to $\hat{q}$

Single scattering of the coherent pair within t_f

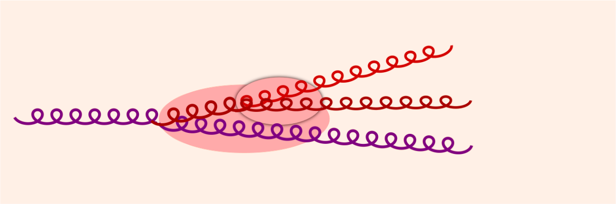


Double logarithmic enhanced contribution

$$\langle p_\perp^2 \rangle_{rad} = \alpha \hat{q} L \int_{l_0}^{L} \frac{dt_f}{t_f} \int_{\hat{q}z}^{\hat{q}L} \frac{dk_\perp^2}{k_\perp^2} = \frac{\alpha}{2} \hat{q} L \ln^2 \frac{L}{l_0}$$

2 Radiative correction to $\hat{q}$

Leading log resummation: arbitrary n-gluon emission



$$\langle p_\perp^2 \rangle_{tot} \approx \hat{q} L \sum_{n=0}^{\infty} \frac{(\alpha \ln^2 \frac{L}{l_0})^n}{(n+1)!n!} = \hat{q} L \frac{I_1(2\sqrt{\alpha} \ln \frac{L}{l_0})}{(\sqrt{\alpha} \ln \frac{L}{l_0})}$$

The lead log result of average energy loss

$$\Delta E_{tot} \approx \frac{\alpha_s N_c}{12} \langle p_\perp^2 \rangle_{tot} L$$

2 Radiative correction to $\hat{q}$

In summary

$$\frac{dN}{d^2 p_\perp} = \frac{1}{\pi \langle p_\perp^2 \rangle_{tot}} e^{-\frac{p_\perp^2}{\langle p_\perp^2 \rangle_{tot}}} \text{ with } \langle p_\perp^2 \rangle_{tot} \approx \hat{q} L \left[1 + \frac{\alpha_s N_c}{2\pi} \ln^2 \frac{L}{l_0} \right]$$

Physical interpretation: renormalized $\hat{q}$

$$\hat{q} \to \hat{q}_{tot} = \frac{\left\langle p_\perp^2 \right\rangle_{tot}}{L}$$

One gluon spectrum shall be modified accordingly.

Blaizot & Mehtar-Tani (2014); Iancu (2014).

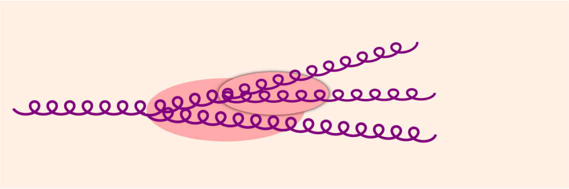
2 Radiative correction to $\hat{q}$

Further discussions

- **Running coupling effects**: see also Iancu & Triantafyllopoulos (2014)

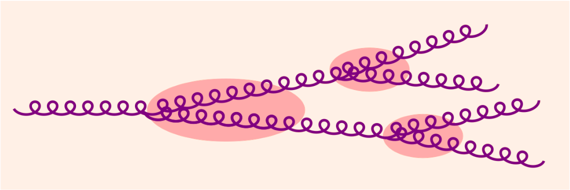
$$\hat{q}_{tot} \approx \hat{q} \left[1 + \frac{\alpha_s(Q_s^2) N_c}{\pi} \ln^2 \frac{L}{l_0} \right] \qquad \text{with } Q_s^2 \equiv \hat{q} L.$$

- **Interplay with vacuum double log:** Mueller, BW, Xiao & Yuan (2016)
- **Partially overlapping emission**: Arnold, Chang & Iqbal (2015-2016)



3 Multiple branching and thermalization

Jet evolution: a game of diffusion, drag and branching

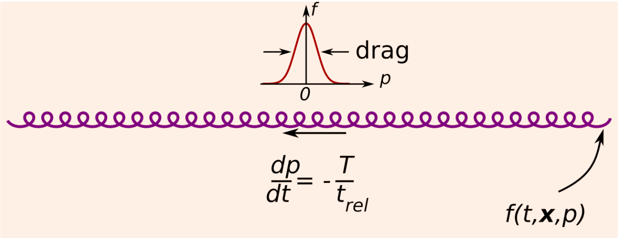


Focus on distribution in the longitudinal phase space!

Iancu and BW (2015).

3.1 Diffusion and drag

Missing effect # 2: drag

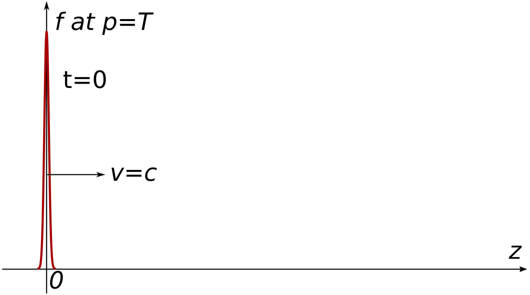


- **The "drag" time:** time for a gluon with momentum p to stop

$$t_{\rm drag}(p) \equiv \frac{p}{T} t_{\rm rel} \qquad \text{with the relaxation time } t_{\rm rel} = \frac{4T^2}{\hat{q}}$$

3.1 Diffusion and drag

What happens to a gluon initially with $p = T$?



- at $t = 0$

$$f = \delta(z)\delta(p - T)$$

- at $t > t_{\rm rel} = t_{\rm drag}$

$$f \simeq \underbrace{\frac{e^{-\frac{|p|}{T}}}{2}}_{\text{thermal}} \underbrace{\frac{e^{-\frac{(z-t_{\rm rel})^2}{4t}}}{2\sqrt{\pi t/t_{\rm rel}}}}_{\text{diffusion in space}}$$

It relaxes into local thermal equilibrium within $\sim t_{\rm rel}$.

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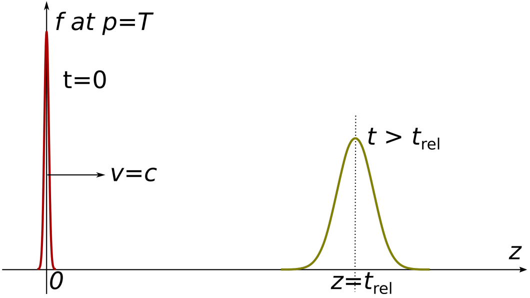

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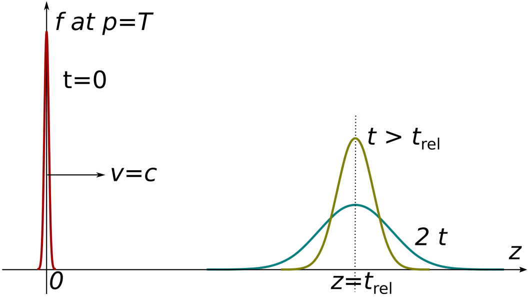

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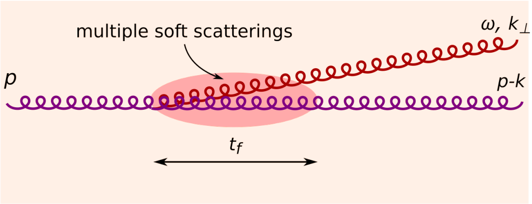
3.2 Branching

The Landau-Pomeranchuk-Migdal (LPM) effect



Formation time:

$$t_f(\omega) = \frac{2\omega}{k_\perp^2} \simeq \frac{\omega}{\hat{q} t_f}$$

$$\Leftrightarrow$$

$$t_f \simeq \sqrt{\frac{\omega}{\hat{q}}}$$

The branching time: $t_{\rm br}(\omega) \equiv \frac{t_f(\omega)}{\alpha} \simeq \frac{1}{\alpha}\sqrt{\frac{\omega}{\hat{q}}}$

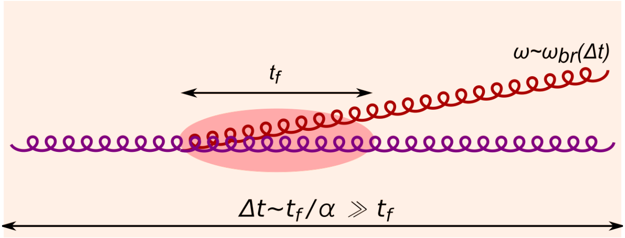
Probability for emitting a gluon with energy ω within t

$$P(\omega, t) \sim \frac{t}{t_{\rm br}(\omega)} \simeq \alpha\sqrt{\frac{\omega t^2}{\hat{q}}}$$

Baier, Dokshitzer, Mueller, Peigne & Schiff & Zakharov (1996-1998).

3.2 Branching

Most probable radiation pattern within Δt



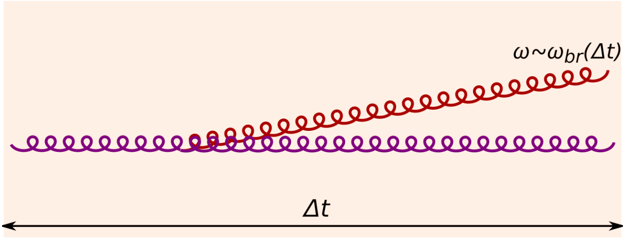
Radiated gluon with $\sim \omega_{\rm br}(\Delta t) \equiv \alpha^2 \hat{q} \Delta t^2$

$$\text{probability} \sim \Delta t / t_{\rm br}(\omega_{\rm br}) \sim 1$$

Baier, Dokshitzer, Mueller & Schiff (2001).

3.2 Branching

Most probable radiation pattern within Δt



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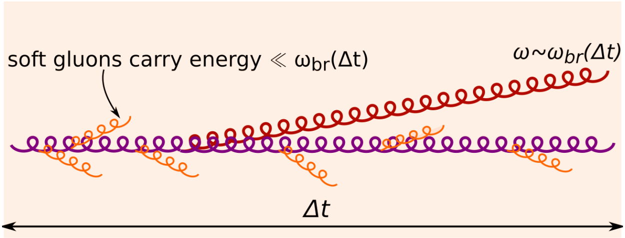
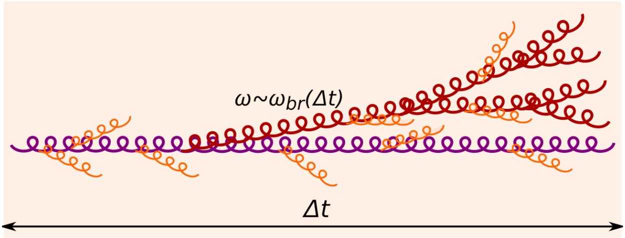


$\Rightarrow$**Typical energy loss** $\sim \omega_{\rm br}(\Delta t) \equiv \alpha^2 \hat{q} \Delta t^2$

Baier, Dokshitzer, Mueller & Schiff (2001).

3.2 Branching

Most probable radiation pattern within Δt



$\Rightarrow$**Typical energy loss** $\sim \omega_{\rm br}(\Delta t) \equiv \alpha^2 \hat{q} \Delta t^2$

Blaizot, Iancu & Mehtar-Tani (2013); Fister & Iancu (2015).

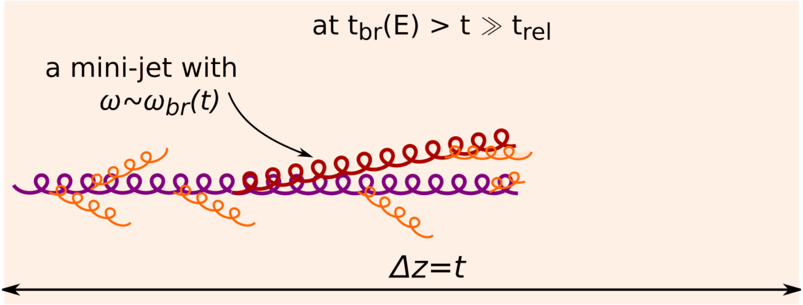
3.4 At $t < t_{\rm br}(E)$

Thermalization of mini-jets with $\omega \lesssim \omega_{\rm br}(t) < E$

Gluons with $\omega \sim T$ are radiated and thermalized within $\sim t_{\rm rel}$.

3.4 At $t < t_{\rm br}(E)$

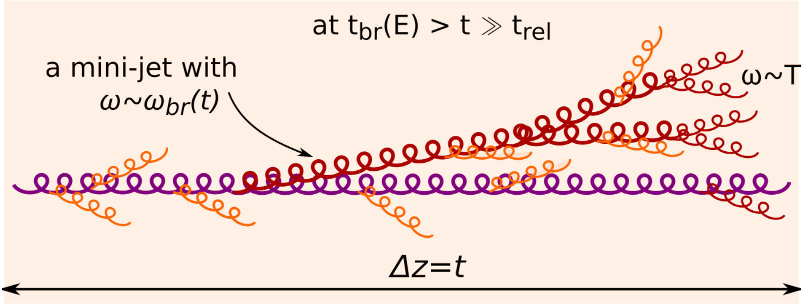
Thermalization of mini-jets with $\omega \lesssim \omega_{\rm br}(t) < E$



Within t, a mini-jet (a gluon with $\omega \sim \omega_{\rm br}(t)$) is emitted.

3.4 At $t < t_{\rm br}(E)$

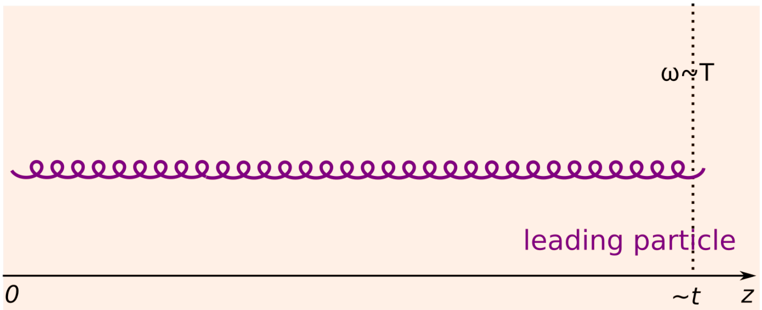
Thermalization of mini-jets with $\omega \lesssim \omega_{\rm br}(t) < E$



The mini-jet branches into soft gluons with $\omega \sim T$ within $\sim t$.

3.4 At $t < t_{\rm br}(E)$

Categorization of gluons:



non-thermal front with leading particle and thermal tail

3.4 At $t < t_{\rm br}(E)$

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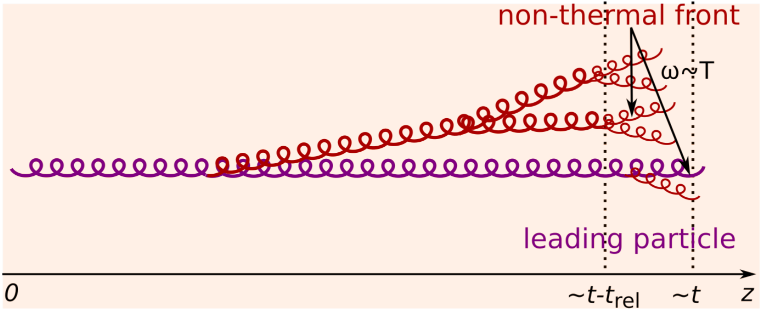

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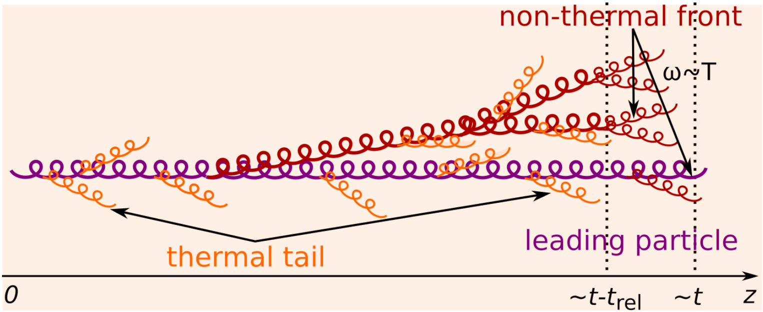
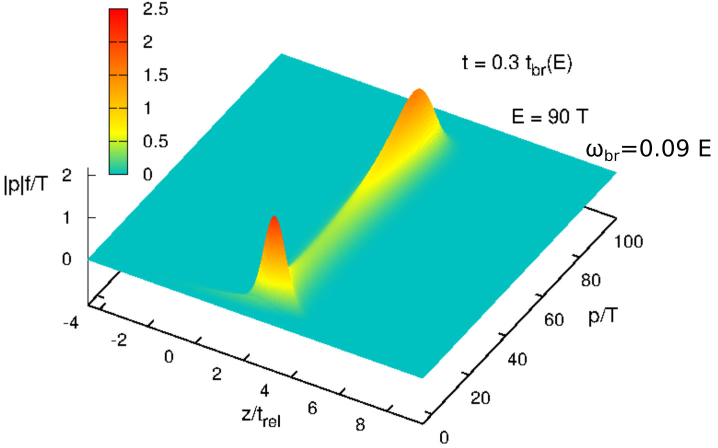


non-thermal front with leading particle and thermal tail

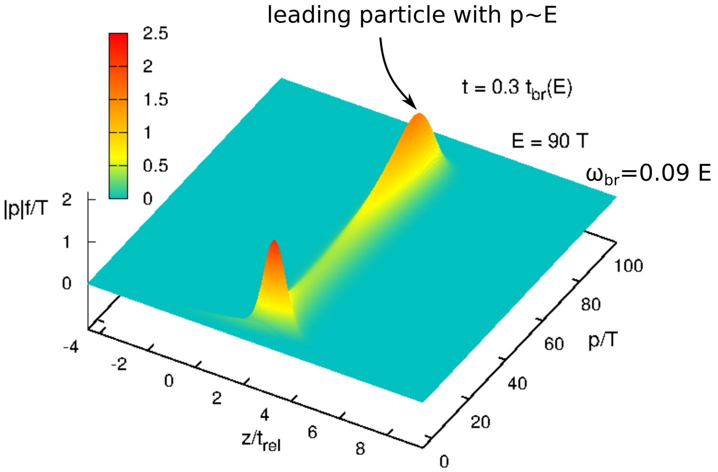
3.4 At $t < t_{\rm br}(E)$

The distribution f at $t = 0.3t_{\rm br}(E)$ with $E = 90\ T$



3.4 At $t < t_{\rm br}(E)$

The distribution f at $t = 0.3 t_{\rm br}(E)$ with $E = 90\ T$



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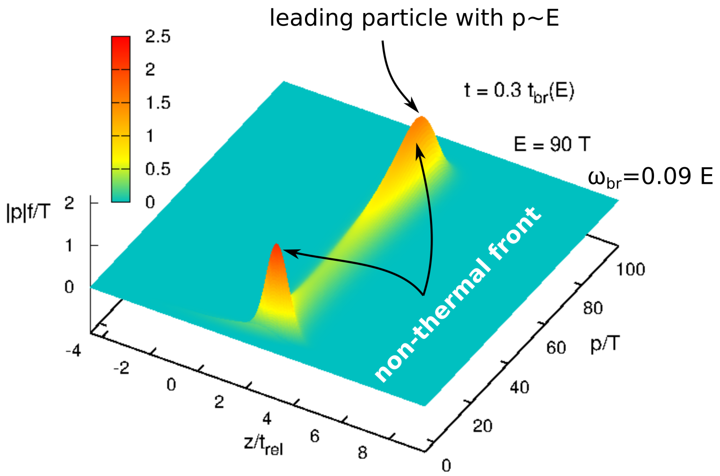

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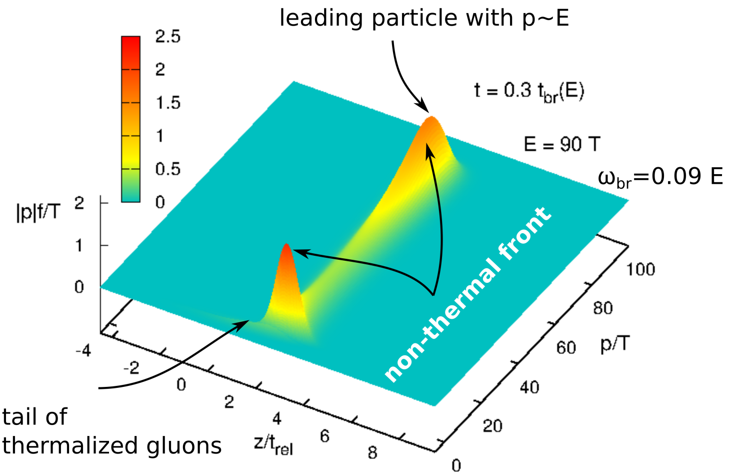
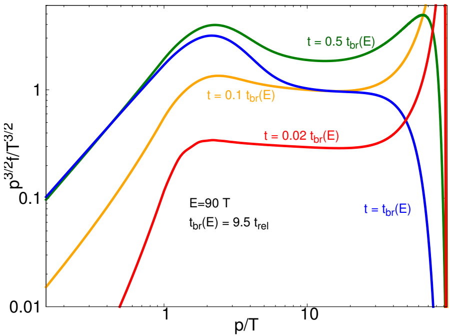


3.4 At $t < t_{\rm br}(E)$

Leading particle peak at $z = t$

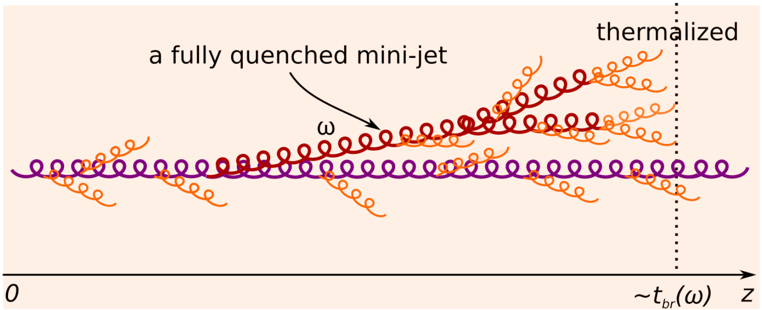


Scaling behavior $f \propto p^{-\frac{3}{2}}$ exists at $z \simeq t \lesssim 0.5 t_{\rm br}(E)$

See also: Mueller, Schiff & Son (2001); Blaizot, Iancu & Mehtar-Tani (2013); Kurkela & Lu (2014).

3.4 At $t < t_{\rm br}(E)$

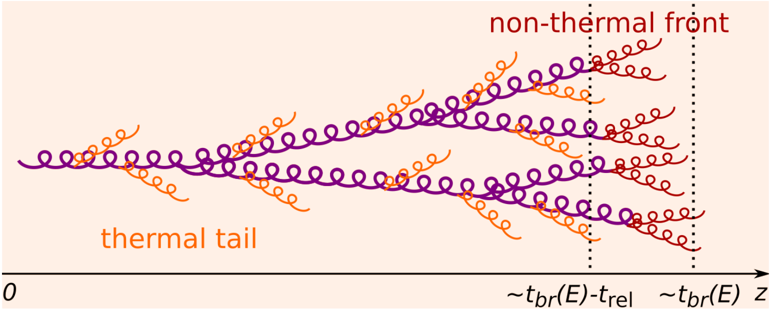
What happens to the mini-jet afterwards?



All its branching products thermalize at $z \sim t_{\rm br}(\omega)$.

3.5 At $t \simeq t_{\rm br}(E)$

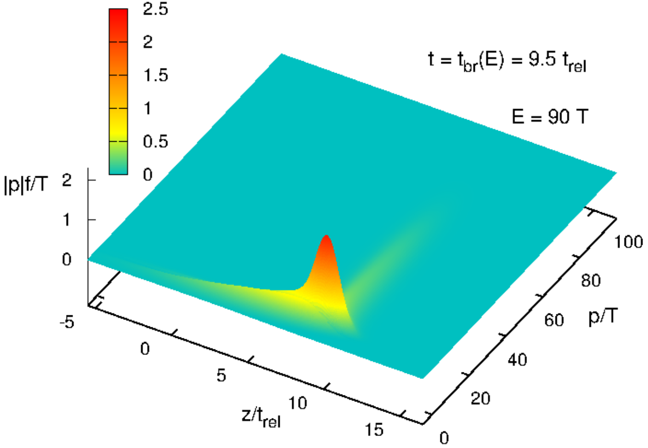
The gluon itself is a mini-jet:



non-thermal front and thermal tail.

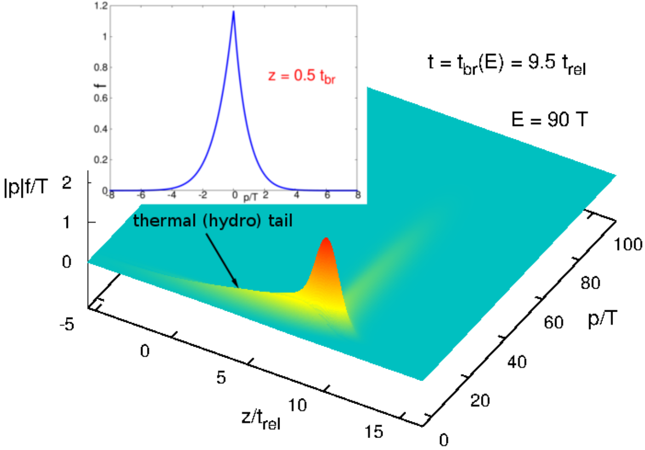
3.5 At $t \simeq t_{\rm br}(E)$

Most gluons with $p \sim T$: non-thermal front + thermal tail



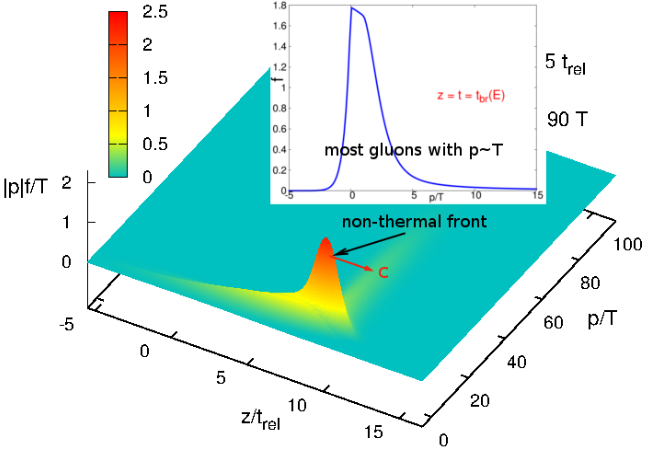
3.5 At $t \simeq t_{\rm br}(E)$

Most gluons with $p \sim T$: non-thermal front + thermal tail



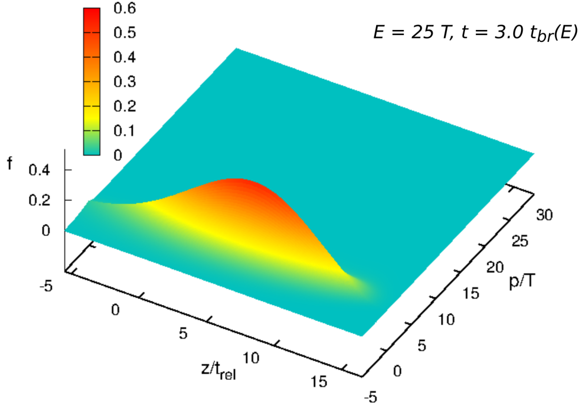
3.6 At $t \simeq t_{\rm br}(E)$

Most gluons with $p \sim T$: non-thermal front + thermal tail



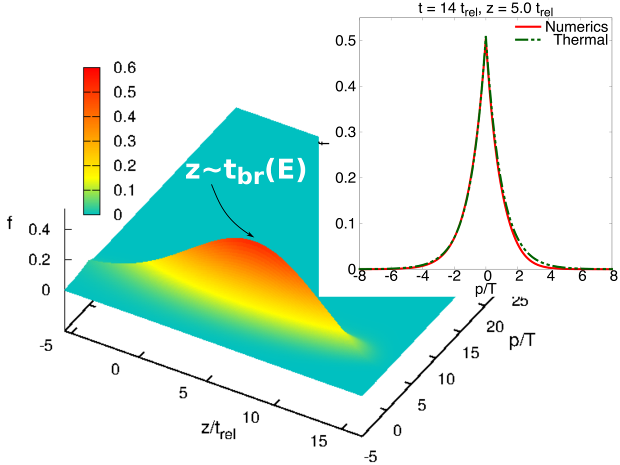
3.6 At $t > t_{\rm br}(E)$

The jet itself is a fully quenched mini-jet.



3.6 At $t > t_{\rm br}(E)$

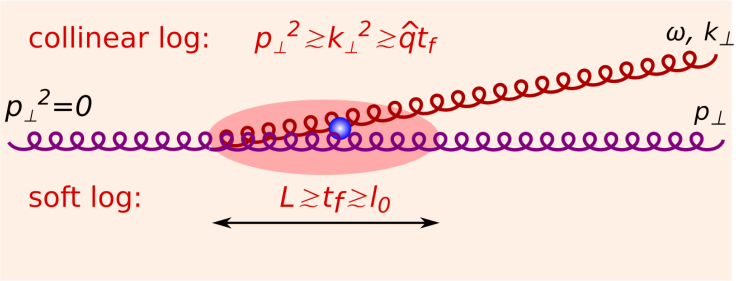
The jet itself is a fully quenched mini-jet.



Summary

Radiative correction to $\hat{q}$

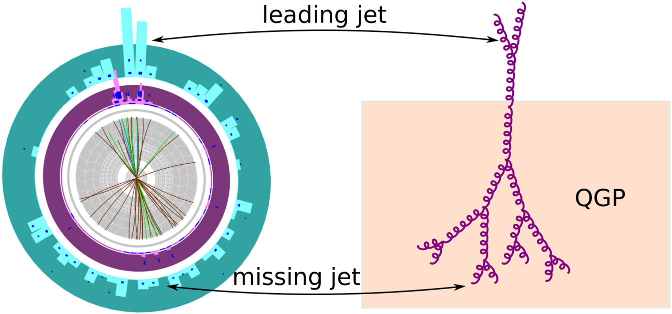
$$\hat{q}_{tot} \approx \hat{q} \sum_{n=0}^{\infty} \frac{(\alpha \ln^2 \frac{L}{l_0})^n}{(n+1)!n!}$$



$\hat{q}_{tot} \approx 1.8\hat{q}$ for $\alpha_s = 1/3, L = 5$ fm & $1/l_0 = 0.3$ GeV.

1.3 Jets in QCD matter

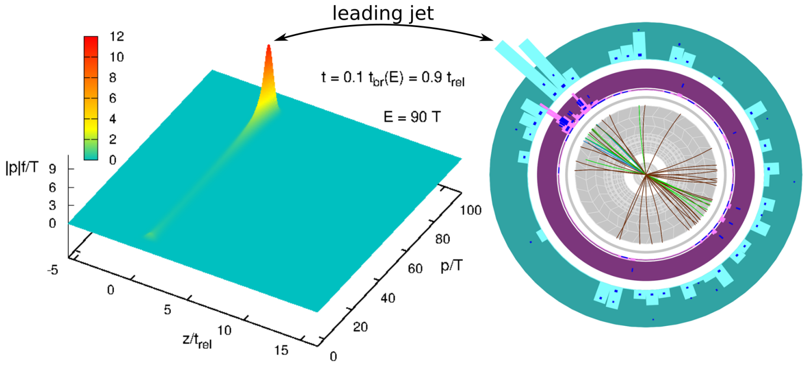
Aim of this talk: the entire evolution of a jet in a QGP



What does this figure mean?

Summary

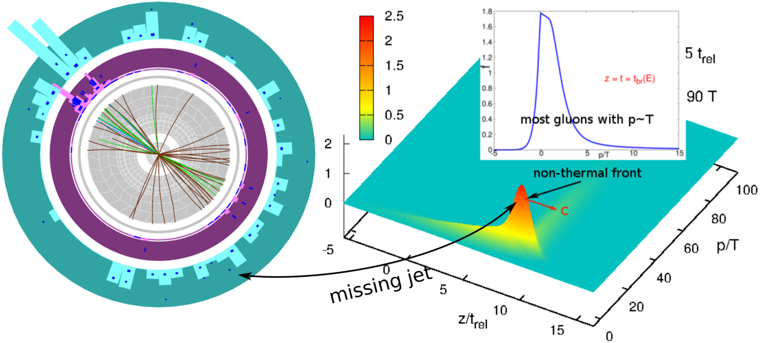
The leading jet



path length $L \ll t_{\rm br}(E) \equiv \frac{1}{\alpha}\sqrt{E/\hat{q}}$

Summary

The missing recoiling jet



path length $L \simeq t_{\rm br}(E) \equiv \frac{1}{\alpha}\sqrt{E/\hat{q}}$